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FULL-SCALE STATIC AND DYNAMIC TESTING OF TIMBER FRAME HOUSES DAMAGED IN THE CHRISTCHURCH EARTHQUAKES

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ABSTRACT: Very little research exists on total house seismic performance. This testing programme provides stiffness and response data for five houses of varying ages including contributions of non-structural elements. These light timber framed houses in Christchurch, New Zealand had minor earthquake damage from the 2011 earthquakes and were lateral load tested on site to determine their strength and stiffness, and preliminary damage thresholds. Dynamic characteristics were also investigated. Various loading schemes were utilised including quasi-static loading above the foundation, unidirectional loading through the floor diaphragm, cyclic quasi-static loading and snapback tests. Dynamic analysis on two houses provided the seismic safety levels of post-quake houses with respect to local hazard levels. Compared with New Zealand Building Standards all the tested houses had an excess of strength, damage is a significant consideration in earthquake resilience and was observed in all of the houses. A full size house laboratory test is proposed.

KEYWORDS: Light timber frame, Seismic response, Full-scale testing, Dynamic assessment

1 INTRODUCTION

It is important to have a comprehensive understanding of the realistic seismic performance of buildings for the design of new buildings, assessment of existing buildings, and repair and upgrade strategies. While stand-alone houses typically have lower importance levels than larger structures, they are still critical structures and if they can retain their use following a large earthquake it can be very beneficial for community resilience. Repairs and replacement of predominantly 1-2 storey timber frame and brick houses after the Christchurch earthquakes cost a total of over NZ $12 billion (USD $9b).

A significant body of research has been done on shear wall testing to determine house stiffness and load resistance provided by the main structural components. In 2014 Kirkham et al. undertook a state-of-the-art review of 200 papers related to Light Timber Frame (LTF) residential structures, and identified 3 static and 3 cyclic pseudo-static tests and 6 shake table tests conducted on near full-scale houses. There were additionally shear wall, horizontal diaphragm, analytical and small size and multi-storey shake table tests reported. Significant findings included the need to better utilise the contribution of gypsum plasterboard panels, to correlate damage with loads, and for more in depth damage reports. [1] This extended the review by van de Lindt in 2004 [2]

Whole-house (LTF) systems include many more contributing aspects and far fewer of these complex tests have been undertaken such as those relevant for Australia and New Zealand [3,4]. Following the series of Christchurch earthquakes in 2010 and 2011 [5] , two-storey blocks of government housing [6] and schools constructed using LTF in New Zealand [7] were tested under fully reversed cyclic loads. Both types of tests have shown that LTF buildings possess significantly greater strength and stiffness than predicted using generally accepted engineering practice. Non-structural elements contribute to higher strength and stiffness, but the actual values need to be better quantified. Some quantification of these contributions was provided through cyclic full-scale laboratory testing of timber infilled walls between steel frames used for New Zealand school gymnasiums [8]. Inclusive full-scale testing of houses can provide more realistic predictions of potential damage and risk, ensure the appropriateness of retrofitting strategies when required, and avoid unnecessary demolitions.

This paper collates the work on lateral load testing performed on five houses that were due for demolition in Christchurch following the earthquakes. Some houses were only moderately damaged where the land was classified as “red zone” and due to high risk of liquefaction and not suitable for long term use, which provided the opportunity for this work. Timber houses provided good life safety with the most widespread damage due to lateral and vertical lateral deformations caused by ground liquefaction. The initial work on the first four of these house tests was reported at WCTE 2014.[9] This paper provides an overview of the test series including discussion of the test methods and results, and describes preliminary dynamic analytical work, details

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the final two-storey test and proposes a full-scale laboratory test for future research.

2 TEST METHODS

The five different houses were tested in different ways. As the testing progressed and more information was obtained regarding the lateral load performance of houses more effective testing strategies were developed. The initial test methodology on the first two houses included loading the house from a beam at the end of the house using diagonally running chain blocks along each side of the houses to provide uni-directional loading applied in steps, including unloading at some stages. Damage was reviewed and recorded in pauses between load increases.

The second test series on two more houses applied full reversed cyclic loads to the houses using hydraulic actuators reacting against constructed reaction frames. The test procedure used a timber flitch beam with double steel inserts that could be added into the ceiling of each house without adding too much mass and thus altering the dynamic responses. Snap-back tests at several different load levels allowed for determination of fundamental frequencies of these two test houses so that dynamic responses could be correlated more accurately with building standards.

Figure 1: *Uni-directional 1993 house snapback test side view.*

Figure 2: *Uni-directional 1993 house snapback test front view showing anchor into slab, sub-slab beam and piles.*

The final test house was loaded uni-directionally using two 7.5T chain blocks (hand winches) attached to a separate concrete foundation (Figures 1-3) and over a pivoting frame through into the first floor diaphragm. The rigidity of the final 2014 load system was increased for this final uni-directional 1993 house test where a reinforced concrete foundation beam and slab were fixed to six screw piles, as shown in Figure 2.
The load system was anchored to two lengths of Reidbar that ran the length of the house and were fastened along their length to 190x45mm timber members. This was then fastened to 20mm thick plywood sheets and attached to the floor at regular intervals to ensure the load distribution was as even as possible. (Figures 3,4)

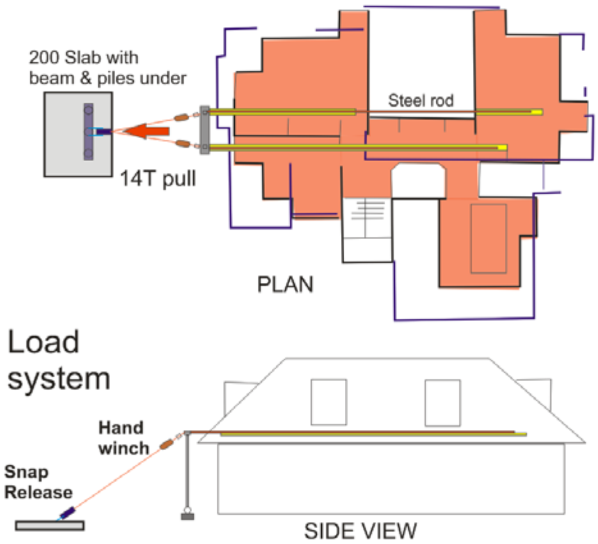


Figure 3: *Uni-directional 1993 house snapback test schematic*

Figure 4: *Uni-directional 1993 house snapback test – anchor system into timber floor diaphragm.*

Load was applied to the house in increments and at each step, new damage to the house was observed and recorded. Five snapback tests were completed in increasing loads, the highest being 80kN. The maximum final quasi-static load was 144kN.

The 1993 house had a very rigid garage wall with considerable torsion under load and had 11mm maximum displacement. Damping varies with deformation and is difficult to identify precisely and was calculated using a hammer blow at lower storey eaves level after the final 144kN load.

All houses tested were instrumented with numerous displacement monitoring gauges to correlate the movements of the buildings with the applied loads. These data allowed for analyses of the load-displacement and dynamic behaviour of these houses.

3 OVERVIEW OF TESTS AND SUMMARY OF RESULTS

The following Tables 1a-1e summarise the house construction, age and type of testing undertaken. The house layouts and load configurations are illustrated diagrammatically. (For the 1993 house the lower level of the two storeys is shown.) The stiffness values are based on quasi-static tests.

TABLE 1 *Summary of Houses and Tests*

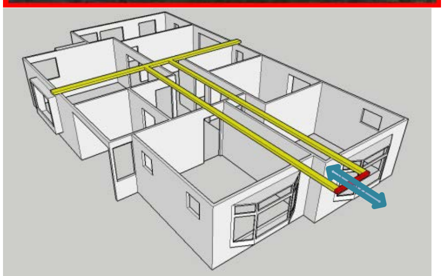
TABLE 1a	1923 – RETREAT ROAD
1 Cladding	Weatherboard
2 Lining	Plaster on lath
3 Floor	Suspended floorboards on piles
4 Foundation	Small upstand on concrete perimeter foundation
5 Year &Test	2013 Hydraulic cyclic & snap-back
6 Photo	
7 Load setup	
8 Built	1923
9 Stiffness / Period	3.8 kN/mm / 0.29s
10 Damping	>15%

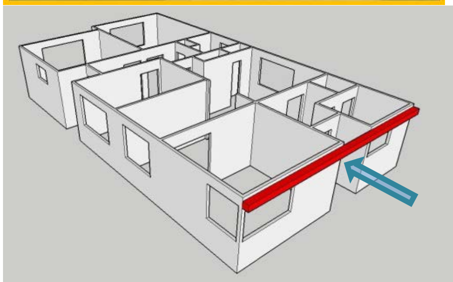
TABLE 1b	1947 - BEXLEY ROAD
1 Cladding	Weatherboard
2 Lining	Fibrous plaster & light timber panelling
3 Floor	Suspended floorboards on piles
4 Foundation	Concrete perimeter foundation
5 Year &Test	2012 - Diagonal uni - directional
6 Photo	
7 Load setup	
8 Built	1947
9 Stiffness / Period	9.0 kN/mm / 0.23s*
10 Damping	-

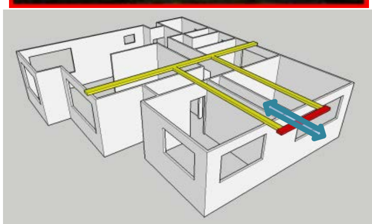
TABLE 1c	1970 - CARDRONA STREET
1 Cladding	Brick Veneer
2 Lining	Gypsum board linings
3 Floor	Suspended floorboards on piles
4 Foundation	Concrete piles, concrete perimeter foundation
5 Year &Test	2013 - Hydraulic cyclic & snap-back
6 Photo	
7 Load setup	
8 Built	1970 +
9 Stiffness / Period	7.5-8kN/mm / 0.20s
10 Damping	>6% (10% by int walls)

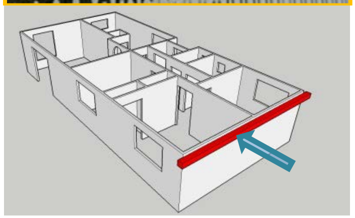
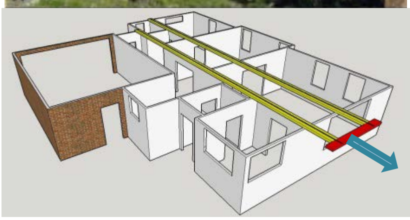
Table 1d	1983 –WAIROA STREET
1 Cladding	Light fibre cement boards
2 Lining	Gypsum board linings
3 Floor	Suspended particle board on piles
4 Foundation	Timber piles
5 Year &Test	2012 - Diagonal unidirectional
6 Photo	
7 Load setup	
8 Built	1983
9 Stiffness / Period	18kN/mm / 0.14s*
10 Damping	-

Table 1e	**1993 -NORCROSS STREET**
1 Cladding	Part brick veneer, part light fibre cement boards, solid brick garage boundary wall
2 Lining	Gypsum board linings
3 Floor	Particle board on timber joist upper floor
4 Foundation	Slab on grade lower floor
5 Year &Test	2014 - Unidirectional & snap– back
6 Photo	
7 Load setup	
8 Built	1993
9 Stiffness / Period	27 kN/mm / 0.14s
10 Damping	2% ambient, ~6% hammer

4 ANALYSIS AND RESULTS

4.1 INITIAL HOUSE TESTS

Maximum loads applied to all but one of the houses were limited by the load system but were well in excess of the previous earthquakes and design levels. Load and displacement data obtained were used to develop strength and stiffness estimates for the tested houses under varying design level earthquakes. Snap-back tests provided dynamic data for some of the houses which allowed for the determination of damping and natural period estimates.

4.2 1993 HOUSE TEST

The 1993 house had two storeys and was the stiffest of the houses tested. With 140kN of load only 7mm of lateral deformation was observed at the upper storey floor level, as shown in Figure 5and was still largely elastic.

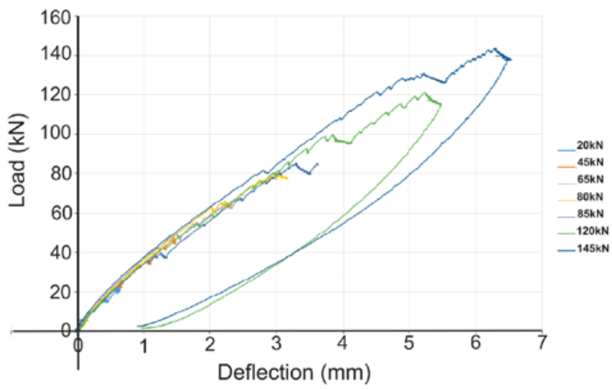


Figure 5. *Load versus displacement for 1993 house*

The stiffness of this house was significantly higher than the 1983 house. The house was incrementally loaded and snapback tests undertaken up to the maximum of the quick release at 78kN. The results of the 78kN snapback test with deformations at multiple locations around the house are shown in Figure 6.

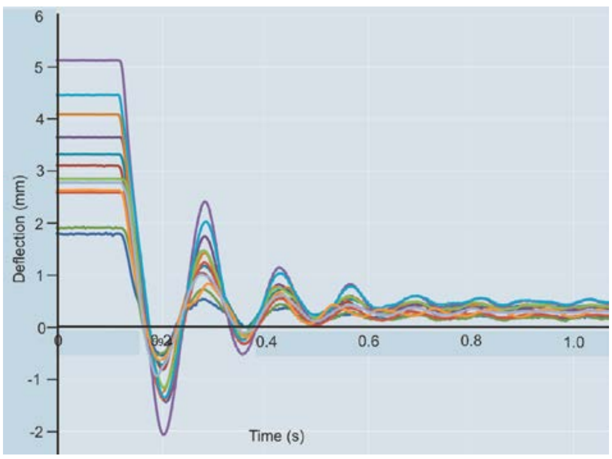


Figure 6: *Dynamic snapback test deformation response at different locations on the 1993 house*

Measuring peak to peak from the graph gave the first modal period in the direction of lateral loading as 0.14

seconds and the approximate damping was calculated at 2%. Using a large hammer to hit the house at the ceiling level gave a damping at this lower magnitude of 6%.

4.3 RESULTS AND ANALYTICAL COMPARISON

Based on the lateral strength and stiffness test results, a seismic fragility review was carried out to develop a better understanding of the seismic safety levels of these post-quake houses with respect to different hazard levels in the Christchurch area. This was done for two houses having a more comprehensive set of load and displacement data and that reached high load and displacement levels [9].

A numerical model was developed and calibrated using the fully reversed cyclic test data, and then seismic simulations were carried out using a total of 19 earthquake records. These records were taken from recording stations around Christchurch from the February 2011 earthquake and were scaled for different return periods using natural periods obtained from snap-back tests of the same house.[9] The simulation results indicated these houses retained very significant residual capacity and performed well under two design levels of earthquakes.

4.4 FRAGILITY

Previous literature on testing and analysis of light timber frame buildings [1] clearly identified that earthquake damage evaluation in houses is needed. One rigorous approach is to develop fragility curves using the numerical approach proposed was by Li in an earlier paper [10]. In addition, damage terms need to be defined relating specifically to LTF buildings at moderate levels of damage. Preliminary work on evaluating damage threshold categories for these houses relevant to fragility curves highlighted there is a level of detail needed in terms of construction type that is dependent on the age of houses. In New Zealand this is made difficult by the large number of houses that have significant alterations over time using varying construction variations which are not easily identified. Each new altered part of a house is built to meet construction regulations in force at the time of the alteration.

There need to have specific criteria developed for common house components. For example the extent of damage to gypsum wallboard has a step change from 2mm cracks which require a minor plaster repair and single wall repaint, to 5mm cracks which likely require a significant part of the room lining be stripped, the attached profiled mouldings removed and replaced, and fittings removed with a full room repaint or refurbishment.

5 DISCUSSION & RECOMMENDATIONS

5.1 INITIAL HOUSE TESTS

The 1983 house test was a simple test on a very simple regular house uni-directionally loaded at one end with chain blocks and reacted from the opposite end above the foundation. It gave useful results and provided confidence to pursue further tests.

The 1947 house was next tested and uni-directionally loaded from one end. This house had residual compression in the framing and it was clear that bi-directional test loading needed to be from the middle of the house.

The 1970 house test was bi-directionally loaded with props to a central beam and used a hydraulic load system. A lightweight beam across the house was assembled in parts within the ceiling space. It was extremely difficult to install in the restricted ceiling space and the load was limited by anchorage within the house and the reaction system.

The 1923 house used the most sophisticated bi-directional hydraulic load system and achieved maximum loads for the structure of the house. The reaction system used piles and 10 tonne cast concrete pile cap beams which restricted the movement of the reaction frame to about 15mm for 250kN maximum load.

5.2 1993 HOUSE TEST METHODOLOGY

The final test used the simplest uni-directional load system and had more reaction capacity with screw piles and a concrete beam and slab. The reaction system was a useful distance from the house because of access to adjacent space. This system could have been duplicated at the opposite end for bi-directional loading if the time had been available.

The access to the full height upper floor and the existence of the existing floor diaphragm gave a major advantage in terms of access and working head height. This type of test methodology would be easiest to replicate for further houses if there is adequate available space.

5.3 ON-SITE HOUSE TESTS

On-site testing in the post-earthquake environment had the added complexity of no power or utilities, restricted access requiring certification and the need to pack up securely against theft and weather every day. On-site testing generally has the significant advantages of testing actual structures with real boundary conditions but has major limitations in terms of the management of load systems and instrumentation.

5.4 LABORATORY TEST RECOMMENDATION

Given the success and limitations of on-site tests a full-scale modest house complete with fittings and non-structural elements such as windows with glass, doors, cupboards and limited interior joinery is proposed.

The initial design was proposed to fit within the Structures Test Lab at the University of Auckland [11] with potential bi-directional load applied in each direction and then simultaneously using hydraulics from the reaction walls as shown in Figure 7.

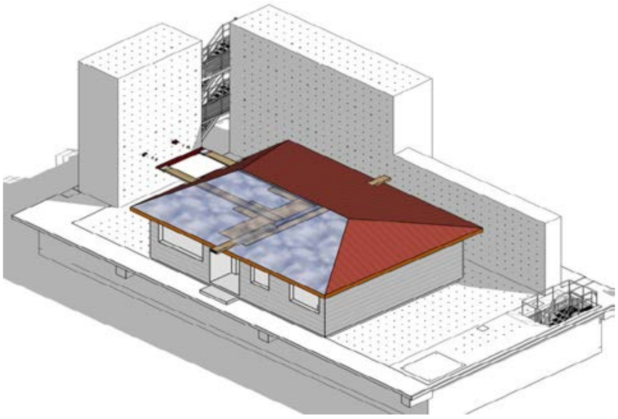


Figure 7: *Illustration of possible house for testing on the strong floor of the Structures Testing Laboratory*

A number of prefabricated houses were investigated and a typical New Zealand house of dimensions that would fit though the opening of the laboratory door was identified.

The house selected shown in an advertising rendering in Figure 8. The rendering has a hip roof but the gable end roof option was selected to fit the load system.

Figure 8: *Rendering of small LTF house as selected for test* (Keith Hay Homes)

Figure 9 shows the standard house plan with the schematic of a lightweight load truss proposed for installation in the ceiling. The truss is designed to have stiffness slightly less than the ceiling diaphragm in each direction. Quasi-static loads would be applied bi-directionally in the initial tests at the points shown.

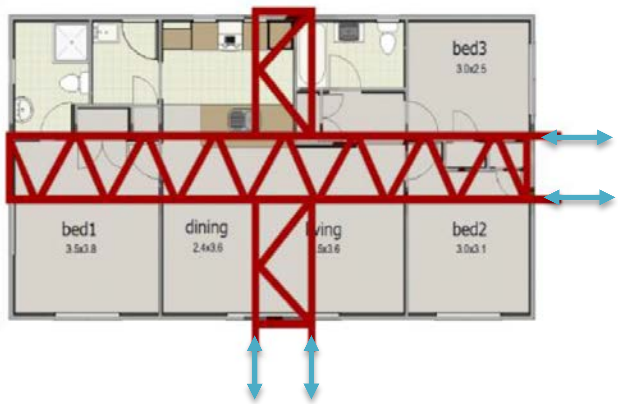


Figure 9: *Load truss overlaid on plan of LTF house with load points shown* (Underlying plan Keith Hay Homes)

The truss is proposed as fibreglass reinforced timber designed for simple assembly to fit around the members of the standard roof truss as shown in Figure 10.It would be anchored at designated points related to the centre of stiffness. Some anchors require detailing for load transfer into the upper wall timbers without laterloading the lower chord of the roof truss.

The truss is to be designed having minimal mass to limit the effects on dynamic response for either snap-back dynamic testing or for an eccentric mass shaker applying load from an adjacent platform.

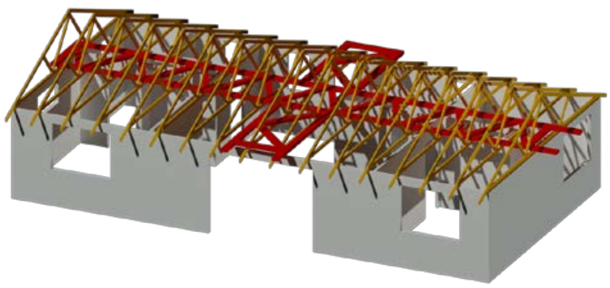


Figure 10: *Illustration of LTF house with load system installed into the roof system.*

These tests will provide a higher level of understanding of the house construction detail with detailed construction monitoring during manufacturing. This will allow some of the truss to be installed prior to installation of the roof cladding and.

Initial dynamic snap release tests would be undertaken to determine natural period and damping and this would be repeated following each quasi-static test at increasing deformation. Once damage is observed it will recorded in detail until damage is observed similar to the typical moderate levels of the other houses and tests.

A fully dynamic test sequence would be undertaken after the detail of the moderate damage is carefully measured. All tests would benefit from the improved precision of laboratory loading, reaction systems and instrumentation.

6 CONCLUSIONS

A successful series of full-scale house tests were undertaken that have confirmed the performance of light timber framed houses and provided the actual data of strength and stiffness, vibration period and damping.

While on-site tests need site specific design, the reaction system and test approach used for the 1993 house was very effective for the snapback tests.

The loads applied to the houses were higher than the earthquake induced loads and the house stiffness's were higher than expected based on the typical New Zealand design parameters.

These data serve as a basis for further analysis to understand seismic fragility but considerable further work is needed.

Following on from this in-situ work, full-house testing is proposed in the University of Auckland laboratory within a controlled and secure environment. A 13m x 7m house has been designed for bi-directional quasi-static loading to determine precise initial damage, followed by dynamic loading to design levels using an offset shaker or dynamic actuators, and quasi-static pushover testing to determine maximum load capacity and post-peak load performance

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8 REFERENCES

[1] Kirkham, W., Gupta, R., Miller, T.: State of the Art: Seismic Behavior of Wood-Frame Residential Structures. *Journal of Structural Engineering*, 140(4): 04013097-1 to 19, 2014

[2] van de Lindt, J. W.: "Evolution of wood shear wall testing, modeling and reliability analysis: bibliography." *Practice Periodical on Structural Design and Construction*, 9(1): 44-53, 2004.

[3] Paevere, P.J.: Full-Scale Testing, Modelling and Analysis of Light-Frame Structures Under Lateral Loading, PhD Thesis, The University of Melbourne, 2002.

[4] Thurston, S. J.: Full-Sized House Cyclic Racking Test. *BRANZ Study Report No. 119*, Building Research Association of New Zealand (BRANZ) Ltd, Judgeford, New Zealand, 2003.

[5] Bradley, B.A. and Cubrinovski, M.: Near-source strong ground motions observed in the 22 February 2011 Christchurch earthquake. *Bulletin of the New Zealand Society of Earthquake Engineering, Special Issue on the 22 February 2011 Christchurch earthquake*, 44 (4). 205-226.

[6] Conner-Woodley, P. Destructive Testing of a Timber Framed "Multi" Unit to Determine Realistic Seismic Assessment Parameters. *2015 New Zealand Society for Earthquake Engineering Conference*, Rotorua, New Zealand, 2015.

[7] Brunsden, D., Finnegan, J., Evans, N., Beattie, G., Carradine, D., Sheppard, J. and Lee, B. Establishing the Resilience of Timber Framed School Buildings in New Zealand. *2014 New Zealand Society for Earthquake Engineering Conference*, Auckland, New Zealand, 2014.

[8] Carradine, D., Beattie, G., Finnegan, J., Brunsdon D., Lee B.Y., and McGuigan, D., Full-Scale Building and Wall Testing to evaluate Lateral Load Performance of Existing Timber Framed School Buildings in New Zealand, *World Conference on Timber Engineering*, Vienna, Austria,2016

[9] Morris H., Beshkyroun S., Smith, T., Li,M., Carradine, D.: In-situ lateral load test performance of Christchurch houses. *Proceedings of the Tenth Pacific Conference on Earthquake Engineering: Building an Earthquake-Resilient Pacific*, Sydney, Australia 2015 (Paper 155 pp. 1-8).

[10] Rosowsky, D.V., Ellingwood, B.R.: Performance-Based Engineering of Wood Frame Housing: Fragility Analysis Methodology. *Journal of Structural Engineering*, 128(1): 32–38, 2002.

[11] Henry, R. S., Morris, H. M., Clifton, G. C., Elwood, K.J., & Ma, Q.T. (2016). Structures testing laboratory at the University of Auckland Newmarket campus. *SESOC Journal*, 29(1), 45-53